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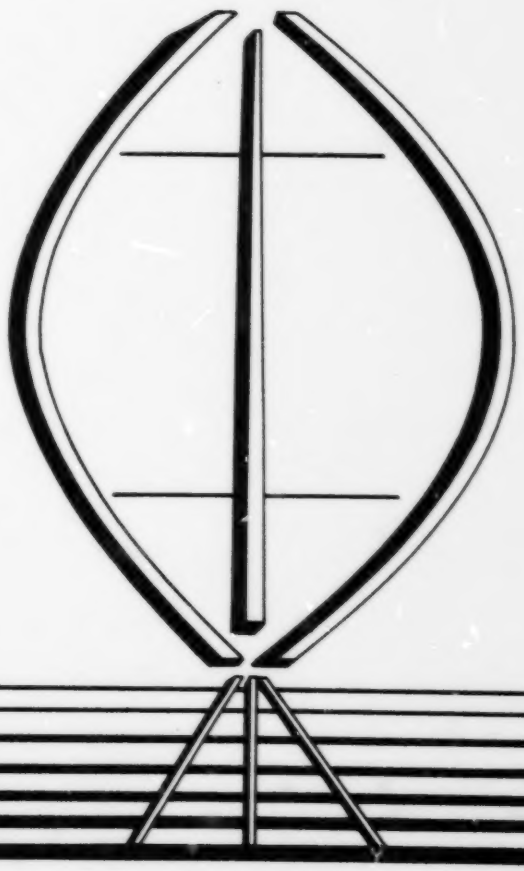
TM-WE-015

Technical Memorandum

Performance of the Holyrood I 50 kW VAWT June 1978 to September 1981

R.S. Rangi

February 1986



Canada

NRCC 27582

87-04602/

Ce projet a reçu l'appui du Comité (fédéral interministériel) de la recherche et du développement énergétiques (CRDE).

This project was supported by the Federal Panel on Energy R&D (PERD).

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PERFORMANCE OF THE HOLYROOD I
50 kW VAWT

June 1978 to September 1981

R.S. Rangi

TM-WE-015
NRCC No. 27582

February 1986

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SUMMARY

A prototype 50 kW vertical axis wind turbine manufactured by DAF Indal of Mississauga, Ontario, was installed near Holyrood, Newfoundland, in June 1978 and operated for almost three years.

The turbine produced 21 600 kWh of net energy in 3015 generating hours. The availability of the turbine during the evaluation period (January 1979 - May 1981) was approximately 40%. The poor availability was primarily due to malfunction of small components and subsequent delays in maintenance, repair, or replacement.

The turbine was dismantled in November 1981 and shipped to Ottawa for non-destructive inspection. The inspection was carried out by the Structures and Materials Laboratory of the National Research Council. The inspection revealed little in the way of major structural damage.

A second updated machine was installed at the site in April 1982.

RÉSUMÉ

Un prototype d'éolienne à axe vertical de 50 kW fabriqué par la DAF Indal de Mississauga (Ontario) a été monté près de Holyrood, à Terre-Neuve, en juin 1978 et a été exploité pendant près de trois ans.

L'éolienne a produit 21 600 kWh d'énergie nette en 3015 h de fonctionnement. Le taux de disponibilité pendant la période d'évaluation (de janvier 1979 à mai 1981) à été de 40 % environ. Cette faible disponibilité découle surtout du mauvais fonctionnement de petits éléments et des temps morts subséquents d'entretien, de réparation ou de remplacement.

L'éolienne a été demontée en novembre 1981 et expédiée à Ottawa pour y subir un examen non destructif. L'examen a été fait par le Laboratoire des structures et des matériaux du Conseil national de recherches du Canada. L'examen n'a pas révélé de dommages structuraux importants.

Une deuxième éolienne révisiée a été montée au même emplacement en avril 1982.

LIST OF TERMINOLOGY
(with particular reference to Table 3)

A: The Weibull scale parameter, used to determine the Weibull distribution of wind speed.

ACTUAL INPUT ENERGY: Electrical energy consumed when starting the turbine, and by the turbine controls and accessories.

ACTUAL OUTPUT ENERGY: Gross electrical energy produced by the turbine (actual not estimated).

AVAILABILITY: Percentage of the total time the turbine was in operational condition; i.e., the complementary fraction of % downtime.

AVERAGE WIND SPEED: Average wind speed as determined from a CR-WHR and anemometer.

BETZ LIMIT: Maximum theoretical amount of energy extractable from the wind (59.3% of the energy in the airstream at all wind speeds.)

BETZ EFFICIENCY: Net energy output as a percentage of the Betz Limit.

CONTINUOUSLY RUNNING WIND HISTOGRAM RECORDER (CR-WHR): Wind histogram recorder that continuously records the turbine site wind data.

CUT-IN WIND SPEED: The wind speed at which the turbine will begin generating power.

CUT-OUT WIND SPEED: The maximum wind speed at which the turbine is allowed to generate power. At wind speeds higher than the cut-out, the turbine will shut off automatically.

DOWN TIME: Time during which the turbine is not in operational condition because of maintenance, mechanical failures, electrical failures, time spent waiting for fault diagnosis, and for replacement of parts and service, etc.

ESTIMATED GENERATION TIME: Time, based on CR-WHR data, during which the wind speed is between the turbine cut-in and cut-out wind speeds.

ESTIMATED OUTPUT ENERGY: Amount of gross electrical energy the turbine should have produced (assuming no down time), based on the CR-WHR and the turbine power curve.

ESTIMATED OUTPUT ENERGY (FROM GENERATE-ONLY HISTOGRAM DATA): Amount of electrical energy the turbine should have produced during the actual generation time, based on GO-WHR data and the turbine power curve.

ESTIMATED OUTPUT ENERGY (NO DOWN TIME, NO CUT-OUT WIND SPEED): Amount of electrical energy the turbine should have produced if the turbine had not been limited by either down time or cut-out wind speed, based on CR-WHR data and the turbine power curve.

GENERATE-ONLY WIND HISTOGRAM RECORDER (GO-WHR): Wind histogram recorder that records the wind data only when the turbine is actually generating power (not fitted on HR-I system).

IDLE TIME: Time during which the turbine was turning but not generating any power (wind speed was below cut-in).

K: The Weibull shape parameter, used to determine the Weibull distribution of wind speed.

NET OUTPUT ENERGY: Total electrical energy produced by the turbine minus electrical energy consumed by turbine controls and accessories and for starting the turbine.

OPERATIONAL EFFICIENCY: Actual energy output as a percentage of estimated output energy.

STOP TIME: Time during which the turbine was operational, but was not turning because the wind speed was too low or too high.

TIME EFFICIENCY: Actual generation time as a percentage of estimated generation time.

TOTAL TIME: Total time in test period (nominally a month).

PERFORMANCE OF THE HOLYROOD I, 50 kW VAWT
JUNE 1978 TO SEPTEMBER 1981

R.S. Rangi

1.0 INTRODUCTION

The Holyrood 50 kW vertical axis wind turbine (VAWT) is a joint field trial project between Newfoundland and Labrador Hydro (NLH) and the National Research Council of Canada (NRCC). The installation is at the NLH Holyrood thermal power plant about 30 miles from St. John's.

The first 50 kW VAWT, referred to as HR-I, was installed in mid-June 1978. This report describes the overall performance of this unit over approximately a three-year test period. This turbine was one of the first prototype 50 kW units built by DAF Indal and is described in Section 2.

After initial testing and operation in manual mode for about a month, the turbine was put into automatic mode but operated only when attended. The turbine was cleared for unattended operation in the automatic mode at the beginning of December 1978 and handed over to NLH for evaluation on 2 January 1979.

In Section 3, the operational history of the turbine and the reasons for the large amounts of down time are discussed. The availability of the turbine improved steadily during 1979 and 1980. However, during 1981 its reliability began to deteriorate and more and more effort was required to keep the unit in operation. In the meantime, DAF Indal had developed a new design that combined a step-up gear and mechanical brake, eliminated the aerobrakes, and incorporated a new control and protection system. Two units employing this new design were operating near Victoria, B.C., and in California with very high availability. In May 1981 at a meeting attended by DAF, NLH and NRCC, after discussing various alternatives it was concluded that it would be more economical to replace HR-I with a machine of new design than to retrofit it with the new design changes. The Holyrood I VAWT was taken down, dismantled, and shipped to NRCC in November 1981 and a new machine referred to as Holyrood II was installed atop the same tower in May 1982.

The site wind data and turbine performance summary for the evaluation period January 1979 to May 1981 discussed in Section 4.

The Holyrood I rotor was subjected to a thorough non-destructive inspection in the Structures and Materials Laboratory of the NRCC. The

results of this inspection are published in ref. 1 and a brief description is given in Section 5.

The conclusions and recommendations based on approximately three years of operation of the HR-I at Holyrood are discussed in Sections 6 and 7, respectively.

The results of the HR-II evaluation are the subject of another report (see ref. 3).

2.0 DESCRIPTION OF THE HR-I 50 kW VAWT

2.1 General

The HR-I VAWT, see Figures 1 and 2a, had a 16.8 m × 11.2 m (55 ft × 36.6 ft) rotor with two 0.356 m (14 in.) chord blades. The blades were made from aluminium extrusions of NACA 0015 airfoil section. The rotor was mounted on a 9.1 m (30 ft) steel tower and held in place with four 22 mm (7/8 in.) diameter steel guy wires. The transmission consisted of a Hansen gear box with 15:1 gear ratio, and a toothed belt and pulley drive with a 1.45:1 ratio between the gearbox and the 75 HP induction motor/generator (see Figure 2c). For a list of physical and geometric data see Table 1.

The turbine was first operated at 90 rpm but in December 1978 the rotational speed was reduced to 82.7 rpm as the turbine was producing more than 60 kW in high winds at 90 rpm. The change in the speed ratio was made by changing the pulley sizes.

2.2. Disc Brake

The HR-I was equipped with a disc brake on the low speed shaft. The brake could be applied manually or automatically by the protection system. The brake pads were operated hydraulically with pressure supplied from a nitrogen bottle by opening a solenoid valve, see Figure 2b. This solenoid valve was held in the closed position with power "on" so that if power to the solenoid was interrupted, by the control system or accidentally, the brakes would be applied automatically.

2.3 Aerobrakes

The turbine was also fitted with two aerobrakes, or spoilers, one on each blade, at the equator. These aerobrakes were held in the closed position by two independent latching mechanisms. In case of overspeed of the rotor the centrifugal force on two bob-weights, through suitable linkages,

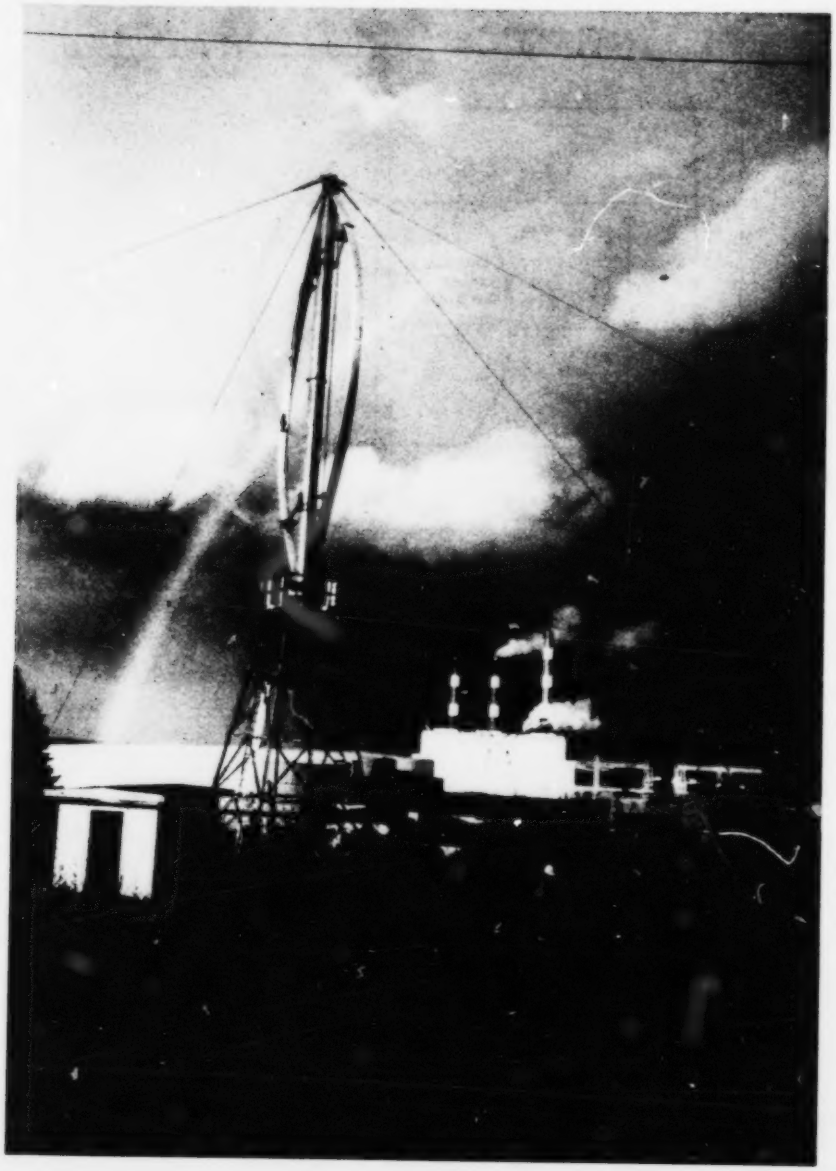

Figure 1. Holyrood I VAWT Installation

would unlatch the aerobrakes. The aerobrakes were then opened by the centrifugal force. The aerobrakes could also be deployed with a push button manually or on command by the protection system. In such cases a pneumatically operated arm would swing out deflecting the bob-weights and unlatching the aerobrakes. The above-mentioned arm was activated by nitrogen pressure supplied by opening a solenoid valve in the same way as in the braking system, see Figure 2b.

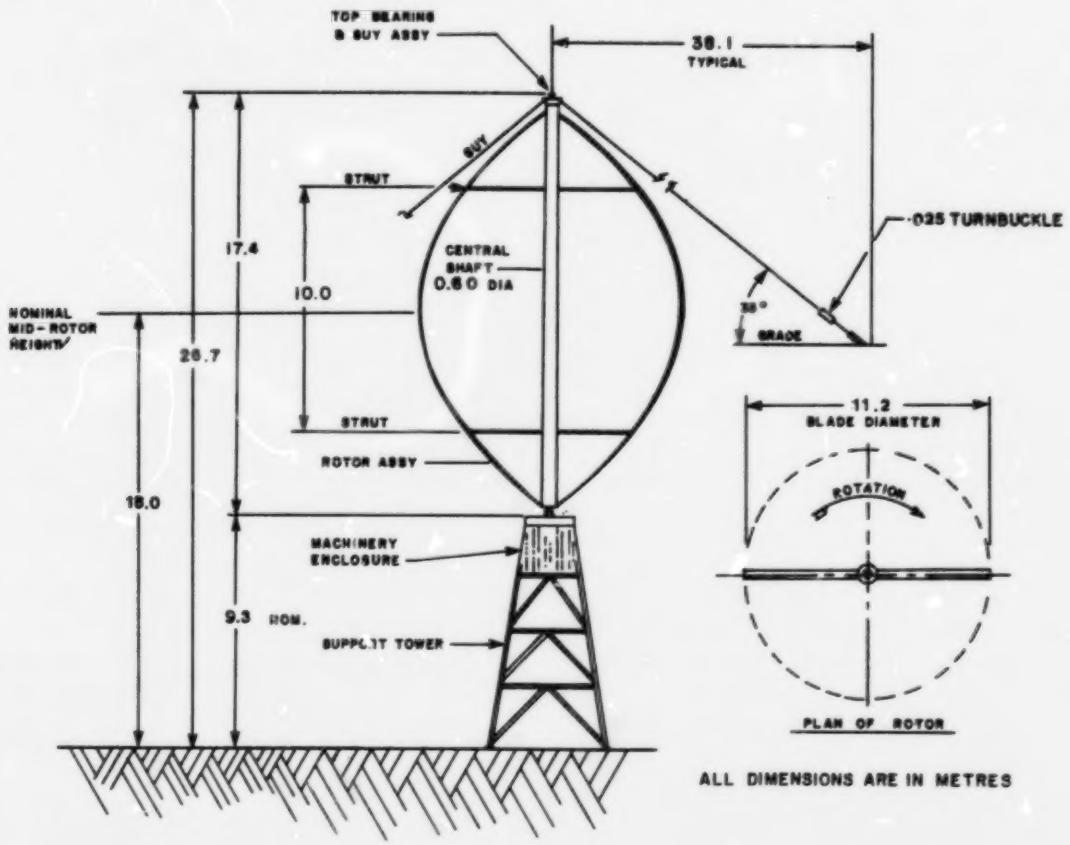

Figure 2a. General arrangement Holyrood I - VAWT

The aerobrakes, once deployed, could only be closed manually.

2.4 Control and Protective System

The control and protective system was designed to allow operation either in a manual or an automatic mode. The protection circuits were active in both modes. The machine could not be started if a fault existed.

In the manual mode the turbine was started by means of a push button. The start was achieved by applying line voltage to the motor/generator in order to rotate the rotor from the stopped position. As the rpm increased, aerodynamic forces on the rotor would assist the motor/generator (M/G) and, if there was sufficient wind, carry the M/G above synchronous speed thus changing the M/G from motoring to generating mode. The turbine could be stopped manually by pushing either the "normal stop" button or the

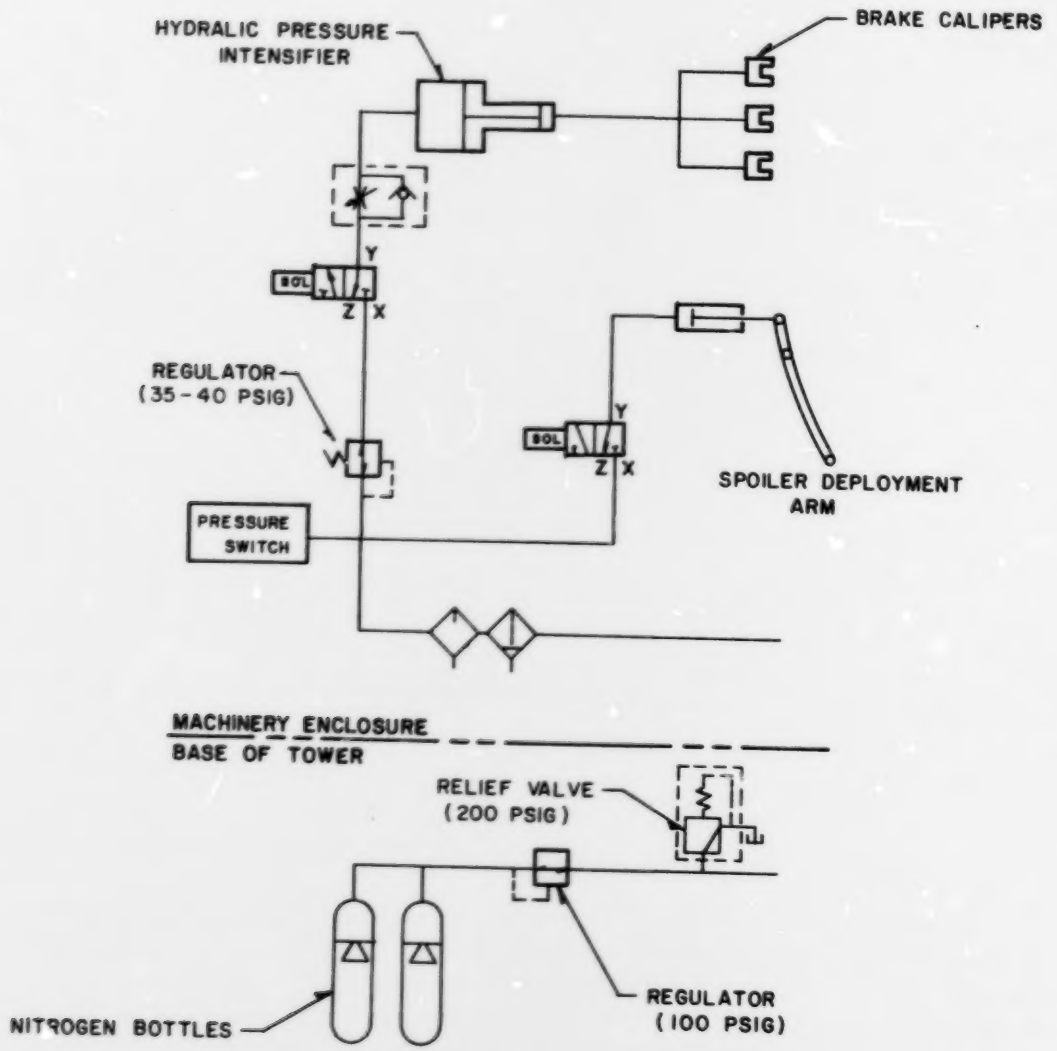

Figure 2b. Disc Brake/Spoiler Deployment System Holyrood I - VAWT

"emergency stop" button. In the case of "emergency stop," the aerobrakes were also deployed.

In the automatic mode, the normal mode of operation, the turbine would start up if the wind speed was above the cut-in wind speed for a specified period (about 2 min). The turbine would shut down automatically if the wind speed exceeded the cut-out wind speed for a specified period, or if the motor/generator consumed power longer than a specified period. In case of a "fault" detection during operation the protection system always initiated an "emergency stop." All emergency stops required clearance by the operator before another start could take place.

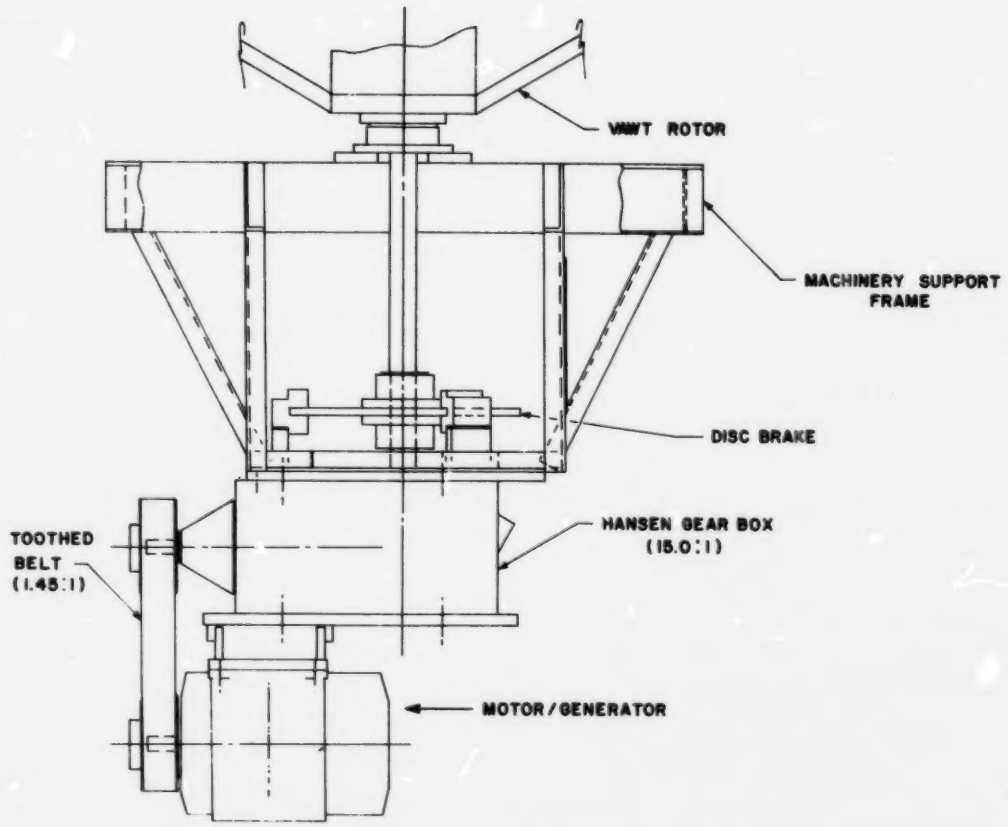

Figure 2c. Drive Train Schematic Holyrood I - VAWT

As mentioned above, initially the control logic would shut down the turbine if it consumed power for about 2 min. However, this logic was soon changed to incorporate the "idle" mode. In the idle mode the motor/-generator was taken off line if it consumed power and the turbine was allowed to rotate, or idle, instead of being stopped by braking. While in the idle mode, if the wind speed picked up, the system would reconnect to the line the moment the turbine reached synchronous speed. On the other hand, if the wind speed diminished and the turbine rpm dropped below a set value the machine was shut down using the "normal stop" procedure.

A guy tension monitoring system was also incorporated into the control system. The turbine was shut down if the guy tension, static or dynamic, exceeded the specified high or low tension.

The control logic was also later modified to incorporate the so-called "resurrection" mode. Prior to this modification if the turbine was shut down due to some non-emergency condition (e.g., loss of power on the

Table 1. HR-I VAWT - Geometrical and Physical Data

ROTOR

Height = 16.8 m (55 ft)
Diameter at equator = 11.2 m (36 ft 8 in.)
Speed = 82.7 rpm
No. of struts = 2, 9.1 m apart (30 ft)

ROTOR COLUMN

Height = 16.8 m (55 ft)
Diameter = 61 cm (2 ft) O/D
Thickness = 6.4 mm (0.25 in.)
Material: Spiral-welded steel tube
Weight = 3628.7 kg (8000 lb)

ROTOR BLADES

Airfoil: NACA 0015
Chord = 35.6 cm (14 in.)
Cross-section area = 50 cm^2 (7.75 $in.^2$)
Material: 6063 -T6 aluminum
Length = 20.8 m (68 ft)
Weight = 13.84 kg/m (9.5 lb/ft)

AERO BRAKES

Number: 2
Area (total) = 0.88 m^2 (9.5 ft^2)

GUY WIRES

Number: 4
Length = 46.3 m (152 ft)
Diameter = 2.2 cm (0.875 in.)
Angle with ground = 35°
Structure: 19 galvanized steel strands
Breaking Strength = 41 730.5 kg (92 000 lb)

TRANSMISSION

Manufacturer: Hansen
Gearbox ratio: 15:1
Spur gears and helical gears
Belt drive ratio 1.45 to 1 (adjustable by changing pulleys)

TOWER

Height = 9.1 m (30 ft)
Base = 4.9 m × 4.9 m (16 ft × 16 ft)

GENERATOR

Rated power = 56 kW
Speed = 1800 rpm
Type = Squirrel-cage induction, 3-phase, 575 V, 60 cycle

transmission lines to the site) the turbine would remain shut down unless an operator cleared it for restart. With the incorporation of the resurrection mode, after a shut down, the control system would test every half hour to determine if the fault remained. If the fault was rectified, or disappeared, the turbine would self start provided there was sufficient wind. The resurrection circuit could not start the turbine if it had stopped due to some emergency situation (e.g., overspeed) since the aerobrakes were always deployed in emergency stops and could only be closed manually.

In addition to the above modifications, a number of clocks or counters were also added to the control system to help evaluate the performance of the turbine.

3.0 OPERATIONAL HISTORY

The turbine was installed in June 1978. At first the machine was operated by a DAF field engineer in manual mode only while attended. The turbine was put into automatic 24-h unattended operation in December 1978. The turbine was still visited by the DAF field engineer during working hours. As the machine was beginning to perform reasonably well it was decided to hand over the turbine to NLH on 2 January 1979 for an evaluation period of one year. The test period was later extended, by mutual agreement by NLH and NRC, in an attempt to obtain one year of trouble-free data. In the early part of 1981 it became clear that the turbine would require major revisions to increase availability to an acceptable level. The machine was dismantled in Novemeber 1981 and shipped to NRC for inspection. The inspection did not uncover any serious structural damage (see ref. 1).

The turbine HR-I was operated for approximately the first 6 months in a commissioning phase, and then for nearly 29 months in the evaluation phase, for a total of approximately 3 years. The major components of the turbine, i.e., the rotor, the drive train, and the motor/generator operated essentially trouble-free over this period. The main subsystems that were responsible for most of the down time of the turbine were:

(a) Brake System:
  (i) Leaky solenoid valves
  (ii) Sticking of brake pads in the "on" position, i.e., failing to retract.

(b) Aerobrakes:
  (i) Leaky solenoid valves
  (ii) Lack of repeatability of the aerobrake deployment rpm due to complicated trip mechanism.

(c) Control and Protection System:

(i) There were innumerable shut downs due to the guywire tension monitoring system, few if any of which were for real causes.

(ii) Malfunctioning of the tachometer used for the control system.

(iii) A new guy tension monitoring circuit and resurrecting control circuit were added and many other minor logic changes were made to the control system. As a result of these modifications the system became very complex and caused many unnecessary shut downs. The control system was removed and rebuilt but the problem still existed.

The history of the down time and causes are listed in Table 2. It should be mentioned here that in many cases a small faulty part resulted in a considerable down time. Sometimes the delay was due to slow delivery of parts and sometimes the delay was caused by the distance involved and shortages of experienced staff.

Table 2 - Operational History

Month	Down Time (h)	Remarks
June 1978	N/A	- down time due to malfunctioning tachometer and replacement with a temporary unit
July 1978	N/A	- down time due to spoilers, brakes, control system - spoiler release mechanisms malfunctioning - brake pads sticking - frequent trips due to rotor overspeeding - several unusual clanking noises - minor problems with pen recorders
August 1978	N/A	- down time due to spoilers, tachometer - continuing problems with spoiler release mechanisms necessitated removal - new mechanisms designed, built and installed - temporary tachometer replaced
September 1978	N/A	N/A
October 1978	N/A	- problems with guy wire vibration developed during a severe storm
November 1978	N/A	- down time due to brake pad wear, a 200-h inspection and overhaul - leaking brake

Table 2 - Operational History (Continued)

Month	Down Time (h)	Remarks
		valve - problems with wear in a loose strut connection
December 1978	N/A	- down time due to spoiler, brakes, control system - brake valve sticking at low temperature and leaking - spoiler valve sticking at low temperature - both replaced with valves of different type - a circuit board in the control system had a broken connection. Larger spoilers installed.
EVALUATION PERIOD STARTED		
January 1979	490	- down time due to control system, spoilers, wind histogram recorder (WHR), guy tension monitor system - frequent emergency stops due to 30 mph cut-out wind speed - crack in spoiler valve sealed with epoxy cement - WHR counting fast - faulty cable causing trouble in guy tension monitor system
February 1979	420	- down time due to spoilers, high winds, guy wires - spoiler relay out - frequent trips due to high winds and high guy wire tension
March 1979	568	- down time due to spoilers, brakes, guy wires - spoiler retaining bolt fell out - replaced - brake valve sticking open - brake nitrogen bottle had to be replaced - frequent trips due to high guy wire tension
April 1979	428	- down time due to guy wires, spoilers, shunt trip relay - frequent trips due to high guy wire tension - spoiler nitrogen bottle and valves sticking - shunt trip relay malfunctioning
May 1979	329	- down time due to NRC inspection of turbine, frequent shunt trips

Table 2 - Operational History (Continued)

Month	Down Time (h)	Remarks
June 1979	233	- down time due to inspection of bearings, frequent guy wire tension trips
July 1979	227	- cut-out wind speed raised to 35 mph on July 11 - down time due to brakes, guy tension monitor system - brake pads sticking - brake caliper replaced - load cell in tension monitor system malfunctioning - replaced
August 1979	223 (est)	- main causes: - faulty aerobrake deployment and control system malfunction
September 1979	700	- down time due to increasing control system problems
October 1979	745	- turbine shut down to install a new control system - installation completed October 29 - motor tachometer malfunctioning
November 1979	720	- turbine shut down awaiting tachometer - tachometer installed on November 20 and tested - turbine put into operation November 30
December 1979	267 (est)	- leaky solenoid valves in the nitrogen supply system - turbine attempting starts with aerobrake open
January 1980	429 (est)	- leaky solenoid valves in the nitrogen supply system - failure to switch from Y to Δ and come off line in low winds - turbine attempting starts with an aerobrake open
February 1980	521 (est)	- faulty deployment of one aerobrake and turbine attempting starts with aerobrake open

Table 2 - Operational History (Continued)

Month	Down Time (h)	Remarks
March 1980	523 (est)	- aerobrake deployment as above - turbine shutdown whenever freezing rain occurred
April 1980	441 (est)	- faulty aerobrake trips, guy tension trips in high winds
May 1980	113 (est)	- similar problems as above
June 1980	298 (est)	- new aerobrake deployment system installed near end of month - transient problems in control system
July 1980	727.5	- turbine shut down for control system and aerobrake modifications and testing - low winds
August 1980	633	- turbine shut down from 12 to 22 August for same reasons as in July - aerobrake latching mechanism overhauled and tested
September 1980	242 (est)	- overspeed relay causing aerobrake deployment
October 1980	340 (est)	- as above
November 1980	706	- digital tachometer failed - Y to Δ relay faulty
December 1980	731	- turbine shut down due to problems mentioned above
January 1981	546	- turbine shut down for 15 days for repairs - some down time after repairs due to overspeed relay trips
February 1981	111	- overspeed relay trips due to control system malfunction

Table 2 - Operational History (Concluded)

Month	Down Time (h)	Remarks
March 1981	247	- as above
April 1981	152	- overspeed relay repaired - guy tension trips causing shut down
May 1981	462	- gear box tachometer failed
June 1981	742	- turbine operation suspended
July 1981	676	- as above
August 1981	1245	- as above
September 1981	833	- as above
October 1981		- turbine dismantled

4.0 DATA PROCESSING AND ANALYSIS

During the evaluation period site winds and turbine performance were recorded daily by NLH except on Saturdays, Sundays, and holidays. The data were analyzed by T.E.S. Ltd. of Ottawa under contract to NRCC and the results are presented in Tables 3 a, b, c (see also ref. 2). Definitions of the Table 3 column headings are given in the List of Terminology.

4.1 Site Wind Regime

In Table 3, columns (1) and (2) give the time period and the corresponding nominal month. The next two columns, (3) and (4), give the average wind speed at the site during the period and the value of the Weibull exponent. The value of this exponent defines the shape of the wind distribution curve (see Section 6 of ref. 2). The wind speed was measured with a Climet cup type anemometer located at mid-rotor height approximately 18 m (60 ft) above ground level. The wind speed was binned using a DAF 18 bin wind histogram recorder to obtain the wind speed distribution (ref. 2). The monthly average wind speed for the test period is plotted in Figure 3 and compared with the AES mean monthly average wind data (1950-1980) for St. John's, Newfoundland.

Table 3a. Performance Summary for VAWT Field Trial, Holyrood I, 50kW VAWT

CUT IN WIND SPEED 5.60m/s
CUT OUT WIND SPEED 15.55m/s

YEAR: 1979				ESTIMATED PERFORMANCE (NO DOWN TIME)			ACTUAL PERFORMANCE											
① APPROX. MONTH OF RECORD	② TOTAL TIME IN PERIOD	③ AVERAGE WIND SPEED	④ K	⑤ AVAIL. WIND ENERGY BETZ LIMIT	⑥ EST. GEN. TIME	⑦ EST. OUTPUT ENERGY	⑧ DOWN TIME	⑨ STOP TIME	⑩ IDLE TIME	⑪ ACTUAL GEN. TIME	⑫ ACTUAL INPUT ENERGY	⑬ ACTUAL OUTPUT ENERGY	⑭ ESTIMATED OUTPUT ENERGY FROM GENERATE ONLY HISTOGRAM DATA	⑮ ACTUAL OUTPUT ENERGY % OF AVAIL. WIND ENERGY	⑮ ACTUAL OUTPUT ENERGY % OF EST. OUTPU ENERG (NO DOWN TIME	⑰ ACTUAL GEN. TIME % OF EST. GEN. TIME	⑱ DOWN TIME % OF TOTAL TIME IN PERIOD	⑲ ESTIMATED OUTPUT ENERGY NO DOWN TIME NO CUT OUT WIND SPEED
	h	m/s		kWh	h	kWh	h	h	h	h	kWh	kWh	kWh	%	%	%	%	kWh
JAN.	713	6.5	1.81	23189	337	4437	490	121.8	15.6	65.5	210	350		1.5	8.1	25.4	68.7	5151
FEB.	669	6.9	2.25	18952	350	4376	420	124.1	45.2	79.7	80	610		2.8	12.1	22.7	62.8	4529
MAR.	743	6.5	1.86	20598	348	3937	568	94.1	14.5	66.4	50	540		2.6	13.7	19.0	76.4	4507
APR.	670	5.6	1.63	15487	237	3195	428	157.9	37.1	47.0	30	320		2.0	10.0	19.8	63.8	3558
MAY	728	4.6	1.74	8020	182	1507	329	327.4	24.4	47.2	72	368		4.5	24.4	25.9	45.2	1556
JUNE	727	4.7	2.15	6544	196	1123	233	258.7	30.7	104.6	126	332		4.9	29.5	53.3	32.0	1125
JULY①	743	5.0	1.65	8915	225	1496	227	233.1	131.0	151.9	162	478		5.3	31.9	67.5	30.5	1658
AUG.	769	4.7	1.49	8529	182	1404	223*	224*	202.0	120.0	162	467		5.5	33.0	66.0	29*	1603
SEP.	709	6.6	1.97	17695	339	3640	709	0	0.0	0.2	5	0		0	0	0	100	4072
OCT.	752	5.9	1.82	14795	303	2994	745	0	0.0	6.5	4	20		0.2	0.6	2.2	98	3250
NOV.	724	6.7	1.96	20621	363	4402	720	0	1.0	3.0	17	63		0.3	1.4	0.4	96	4851
DEC.	691	6.1	1.61	17604	273	2931	267*	187*	51.0	185.0	372	1399		7.9	47.7	68.0	39*	3515
SUM.	8638	5.8	1.72	181049	3335	35442	5359	1728	552.5	897.5	1290	4877		2.7	13.7	26.9	62	39387

*Estimated Data.

1. CUT-OUT WIND SPEED RAISED TO 15.65 m/s

Table 3b. Performance Summary for VAWT Field Trial, Holyrood I, 50kW VAWT

CUT IN WIND SPEED 6.60 m/s
CUT OUT WIND SPEED 15.65 m/s

YEAR: 1980				ESTIMATED PERFORMANCE (NO DOWN TIME)			ACTUAL PERFORMANCE						(14)	(15)	(16)	(17)	(18)	(19)
(1) APPROX. MONTH OF RECORD	(2) TOTAL TIME IN PERIOD	(3) AVERAGE WIND SPEED	(4) K	(5) AVAIL. WIND ENERGY BETZ LIMIT	(6) EST. GEN. TIME	(7) EST. OUTPUT ENERGY	(8) DOWN TIME	(9) STOP TIME	(10) IDLE TIME	(11) ACTUAL GEN. TIME	(12) ACTUAL INPUT ENERGY	(13) ACTUAL OUTPUT ENERGY	ESTIMATED OUTPUT ENERGY FROM GENERATE ONLY HISTOGRAM DATA	ACTUAL OUTPUT ENERGY % OF AVAIL. WIND ENERGY	ACTUAL OUTPUT ENERGY % OF EST. OUTPUT ENERGY (NO DOWN TIME	ACTUAL GEN. TIME % OF EST. GEN. TIME	DOWN TIME % OF TOTAL TIME IN PERIOD	ESTIMATED OUTPUT ENERGY NO DOWN TIME NO CUT OUT WIND SPEED
	h	m/s		kWh	h	kWh	h	h	h	h	kWh	kWh	kWh	%	%	%	%	kWh
JAN.	738	6.7	1.75	24617	345	4631	429 *	83	81	145	370	1710		6.9	36.9	42.2	58	5439
FEB.	698	6.3	1.65	22163	307	3852	521 *	81	18	78	74	1006		4.5	26.0	25.5	74.5 *	4747
MAR.	740	6.9	1.95	23364	365	4687	523 *	41	69	107	116	650		2.8	13.9	29.3	71 *	5237
APR.	714	5.3	1.87	11000	246	2376	441 *	93	86	94	175	758		6.9	31.9	38	62 *	2414
MAY	747	4.9	1.89	9181	225	1835	113 *	300	143	191	265	1102		12	60	84.8	15 *	1880
JUNE	711	5.5	1.78	12489	267	2525	298 *	94	164	155	213	1167		9.3	46.2	58	42 *	2735
JULY	728	4.3	1.69	6278	171	1160	727.5 *	0	0	0.5	0	0		0	0	.3	99.7	1187
AUG.	754	4.9	2.02	8296	206	1686	633	78	10	33	105	329		4.0	19.5	16.1	84	1702
SEP.	713	6.1	1.78	16953	292	3487	242 *	180	98	193	197	1912		11.3	54.8	66.0	34 *	3917
OCT.	750	5.8	1.92	13878	293	2987	340 *	128	122	160	148	1176		8.5	39.4	54.6	45.4 *	3128
NOV.	719	6.7	1.59	25134	309	4190	706	7	1	5.4	2	82		.3	1.9	1.7	98	5232
DEC.	741	6.4	1.68	22535	320	4254	731	5	1	4.3	47	10		.04	.2	1.3	99	4957
SUM.	8753	5.8	1.66	195888	3346	37670	5704.5 *	1090	793	1166.2	1712	9896		5.0	26.3	34.9	65.2	42575

* Estimated Data.

Table 3c. Performance Summary for VAWT Field Trial, Holyrood I, 50kW VAWT

CUT IN WIND SPEED 5.60 m/s
CUT OUT WIND SPEED 15.65 m/s

YEAR: 1981				ESTIMATED PERFORMANCE (NO DOWN TIME)			ACTUAL PERFORMANCE						(14)	(15)	(16)	(17)	(18)	(19)
(1) APPROX. MONTH OF RECORD	(2) TOTAL TIME IN PERIOD	(3) AVERAGE WIND SPEED	(4) K	(5) AVAIL. WIND ENERGY BETZ LIMIT	(6) EST. GEN. TIME	(7) EST. OUTPUT ENERGY	(8) DOWN TIME	(9) STOP TIME	(10) IDLE TIME	(11) ACTUAL GEN. TIME	(12) ACTUAL INPUT ENERGY	(13) ACTUAL OUTPUT ENERGY	ESTIMATED OUTPUT ENERGY FROM GENERATE ONLY HISTOGRAM DATA	ACTUAL OUTPUT ENERGY % OF AVAIL. WIND ENERGY	ACTUAL OUTPUT ENERGY % OF EST. OUTPUT ENERGY (NO DOWN TIME)	ACTUAL GEN. TIME % OF EST. GEN. TIME	DOWN TIME % OF TOTAL TIME IN PERIOD	ESTIMATED OUTPUT ENERGY NO DOWN TIME NO CUT OUT WIND SPEED
	h	m/s		kWh	h	kWh	h	h	h	h	kWh	kWh	kWh	%	%	%	%	kWh
JAN.	743	5.4	1.9	15328	255	2681	*2 546	*3 94.4	35	57.6	295	300		1.9	11.2	26.5	*3 73.5	3144
FEB.	670	5.4	1.6	12819	233	2475	111	383	3	113.7	185	635		5.0	25.7	48.6	16.5	2737
MAR.	741	6.6	1.8	23710	334	5029	247	291	77	126	176	1053		4.4	21.0	37.7	33.3	5559
APR.	713	6.5	2.0	17243	352	3610	153	231	85	244	292	1591		9.2	44	69.5	21.4	3301
MAY	708	4.6	1.9	5613	108	1189	462	114	50	82	131	299		4.5	25.1	43.4	65.3	1196
JUNE	742	5.0	2.2	TURBINE OPERATION TERMINATED														
JULY	576	4.8	1.6															
AUG.*1	1245	4.8	1.6															
SEP.*2	033	5.1	1.5															
OCT.				TURBINE REMOVED FROM SITE														
NOV.																		
DEC.																		
SUM.	8339	5.4	1.6	74711	1282	14884	1508	2493.4	310	633.4	1080	3878		5.2	26.1	49.4	42.5	16537
		5.6	1.6	TEST PERIOD AVERAGES														

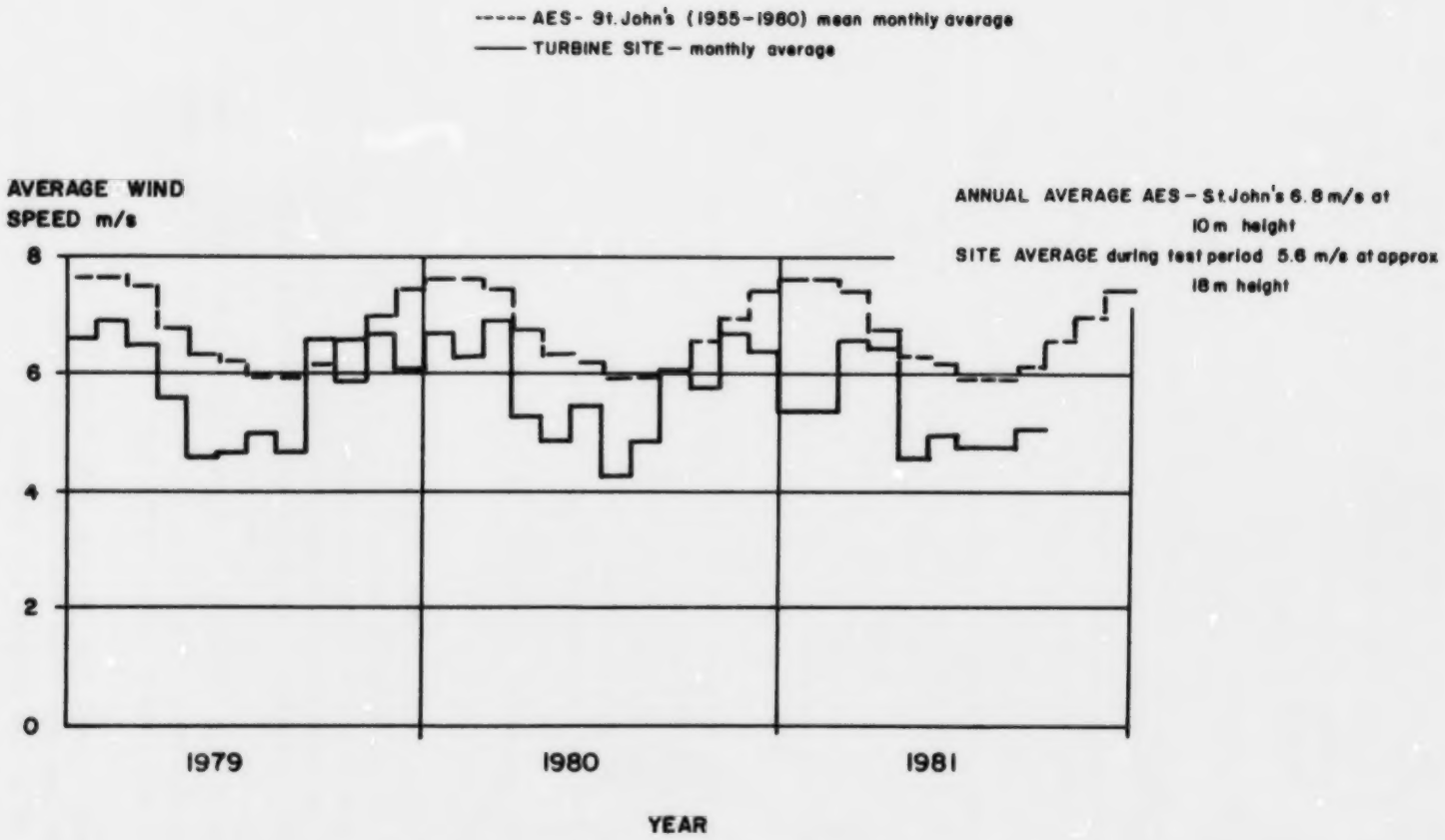

Figure 3. Comparison of Average Wind Speed

It can be seen from Figure 3 that, despite the greater measuring height, the monthly average wind speed at the Holyrood site is generally 1 to 2 m/s lower than the long term average at St. John's Airport. Thus, if the same turbine were to be installed at St. John's the energy output would be about twice as much.

4.2 Turbine Performance

In Table 3, columns (5), (6), and (7) give the estimated performance. The Betz Limit Energy in column (5) is the theoretical maximum energy that could be produced by an ideal, 100% efficient turbine with the same size rotor as HR-I without operating limits or down time (see List of Terminology).

The estimated generate time, column (6), was the time winds were between the cut-in and cut-out wind speed based on the continuously-running wind histogram recorder data. The Estimated Energy Output, column (7), was obtained by multiplying the time in each bin with the corresponding power output of the turbine. The turbine power output curve, see Figure 4, was based on measurements made on the 50 kW machine at Swift Current, Saskatchewan, which was similar to HR-I.

The next six columns (8) to (13) in Table 3 give the Actual Performance of the turbine. There are no entries for down time and stop time from August 1979 to January 1981 because the clocks for the down and stop times were not installed until January 1981. The entries before August 1979 were provided by the DAF engineer then at the site.

As there was no generate-only histogram at this site the 14th column has no entries.

In the next four columns, (15), (16), (17), and (18), the Actual Performance of the turbine is expressed as a percentage of Betz limit or estimated performance. The values in column (15) are the ratio of column (13) and column (5) expressed as a percent. These values give a comparison of HR-I with an hypothetical (100% efficient) machine capable of extracting energy at all wind speeds. It can be seen that actual energy output rarely exceeded 10% of that theoretically available from a perfect system, due primarily to the poor reliability of the equipment and the lengthy diagnostic/logistic and repair times experienced.

The data in next two columns (16) and (17) are the output energy fraction and the generate time fraction, respectively. These values represent the ratios of actual output and generating time to those supposedly achievable by this turbine. The average output energy and generating time

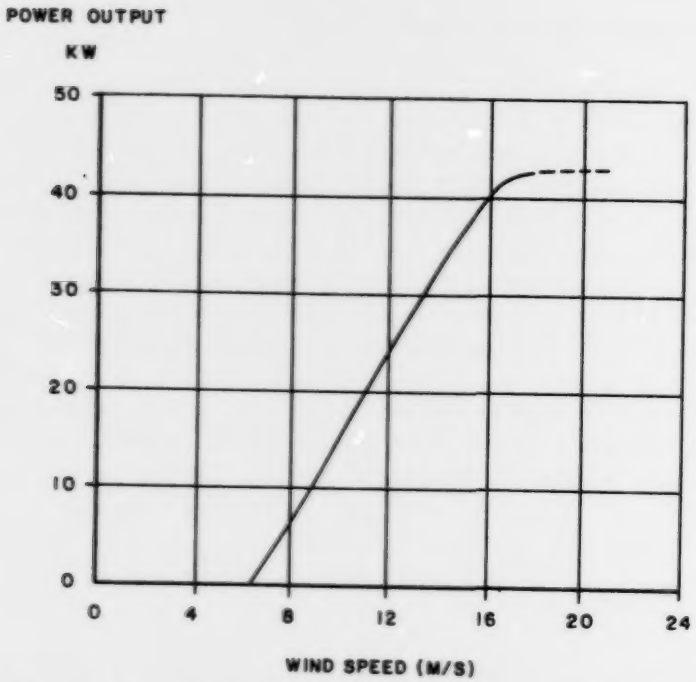

Figure 4. Electrical Power Output at 82.7 RPM.

fractions for the evaluation period were 21% and 33%, respectively. Both the output energy and the generating time are very low and vary drastically from month to month.

The percentage down time, column (18), for the first seven months of 1979 averages 55%. This indicates a very poor availability especially when one takes into consideration the fact that the machine was attended by the manufacturer's field engineer, during daytime hours, and had been operated under his supervision six months prior to that as well. The down time in column (18) is percentage of the time the machine was not in operational status. The overall down time for the period was about 60%. The complimentary ratio to the down time called availability is defined as (1 - down time)%, and is a measure of the operational readiness of the turbine as discussed in Section 4.3.

The last column (19), gives the estimated energy output with no down time and no cut-out wind speed. The only difference between column (19) and column (7) is that column (7) has 35 mph cut-out wind speed and column (19) has no cut-out wind speed. A comparison of data in column (7) and column (19) shows that the estimated energy output of HR-I would have been 11.4% higher with no cut-out wind speed than with the 35 mph cut-out wind speed. This would suggest that the cut-out wind speed could have been raised to 40 mph to reduce the 11.4% loss of energy output.

4.3 Turbine Availability and Energy Output

The monthly availability of the turbine and the monthly estimated and actual energy output of the wind turbine are plotted as bar charts in Figure 5 a and b. The maximum monthly availability during the evaluation period was 85%. Usually the machine performed quite well for a month or two after servicing and then slowly the availability would deteriorate again. The overall availability for the evaluation period was 40%. There are six monthly periods when turbine availability was close to zero. This alone represents 21% of the evaluation period. This is considerable down time for a machine that did not suffer any major breakdown.

The actual energy output and the estimated energy output (no down time) have been compared on month to month basis, see Figure 5. The overall ratio of actual output to estimated output for the evaluation period was 21.2%.

5.0 POST-TEST INSPECTION

The HR-I turbine was dismantled and removed from the Holyrood site during October 1981. All components were shipped to NRCC in Ottawa, where the Structures and Materials Laboratory conducted a detailed examination and non-destrucitve tests of the rotor and guy wire components. The results of this examination (see ref. 1) indicated little major damage. The principal regions of damage appeared to be:

(a) Severe deformation of the holes in the blade strut attachment fittings.
(b) Wear of some of the bolt holes on the blade-end and column-end attachment fittings of the struts.

6.0 CONCLUSIONS

The following conclusions can be drawn from the operating experience and the turbine performance data gathered during the evaluation period (January 1979 to May 1981):

(1) The HR-I turbine had overall availability of 40% and the actual output energy was only about 21% of estimated output for the period.

(2) The major components of the HR-I turbine, i.e., the rotor, the drive train, and the motor/generator, operated essentially trouble-free over the entire period. The main subsystems that required most of the maintenance were:

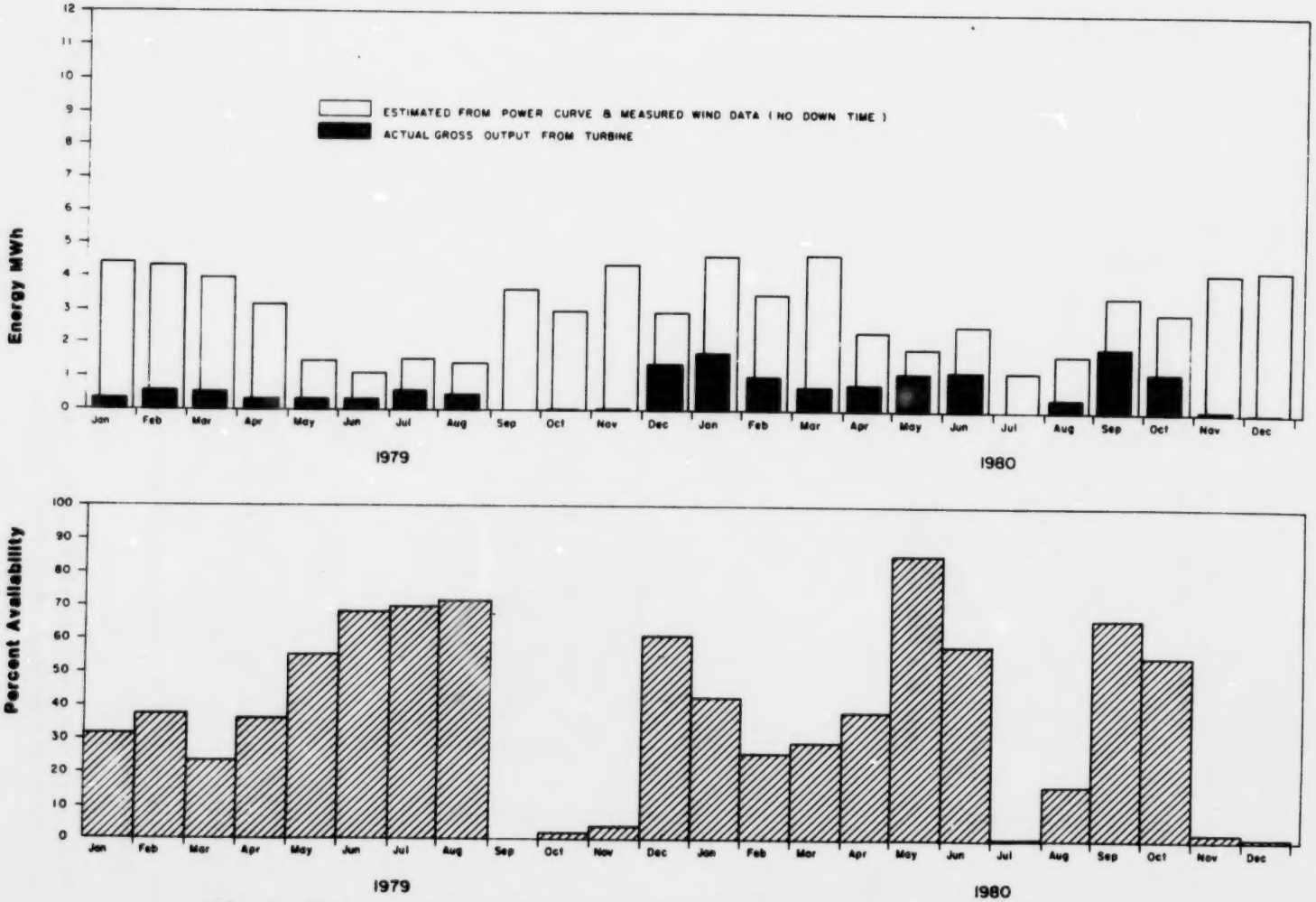
ESTIMATED FROM POWER CURVE & MEASURED WIND DATA (NO DOWN TIME)
ACTUAL GROSS OUTPUT FROM TURBINE
Energy MWh
Percent Availability
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
1979
1980

Figure 5(a). Availability and Energy Production Charts 1979-1980

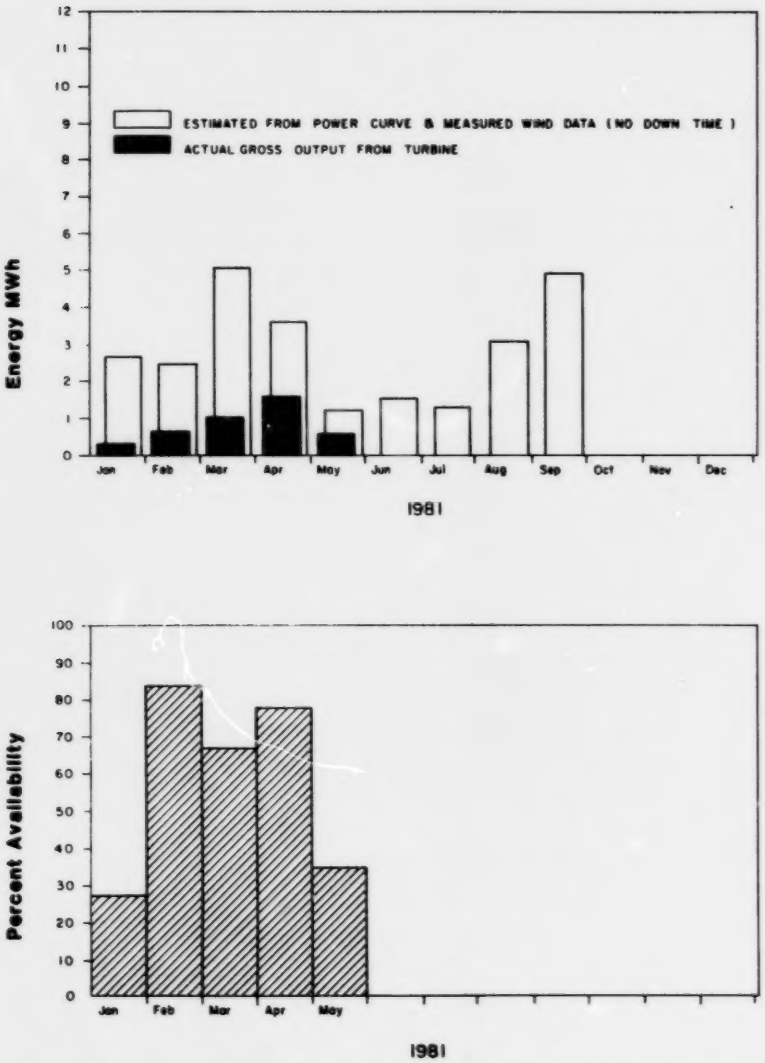

Figure 5(b). Availability and Energy Production Charts 1981

(i) the aerobrake deployment mechanism
(ii) the mechanical disc brake system
(iii) the control system

In most cases only a few small components were the cause of the failure of these subsystems.

(3) There were six periods of at least one month duration during which the HR-I turbine was shut down for repairs.

(4) Considerable down time was due to:
  (i) delay in procuring replacement parts
  (ii) delays in diagnoses, maintenance, or repair
  (iii) lack of a comprehensive operating and maintenance manual

(5) The wind regime at the Holyrood VAWT site is only moderate, as compared, for example, to St. John's Airport where approximately two times the output energy would be obtained from any given wind energy conversion system.

(6) The HR-I turbine after approximately 4500 h of operation (i.e., 3000 h generating and 1500 h idling) and three years of exposure to the environment showed no significant structural damage.

(7) Operating experience gained from the HR-I turbine made a valuable contribution in the development of the following 50 kW turbine designs and to the vertical axis wind turbine program in Canada.

7.0 RECOMMENDATIONS

(1) All components of the turbine should have high reliability. Specifically, care should be taken in detailed design to ensure all subsystems have comparable reliability to the major elements such as the rotor structure, drive train, and motor/generator.

(2) An adequate set of spare parts, especially key components, should be kept at site.

(3) A comprehensive operating and maintenance manual with trouble-shooting instructions should be available at the site.

(4) Ease of service and maintenance should be considered at the design stage.

(5) Arrangements should be made for rapid diagnosis and repair of system malfunctions to avoid prolonged periods of down time awaiting service action.

8.0 REFERENCES

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3. R.S. Rangi and D. Kimbell. Performance of the Holyrood II 50 W VAWT - June 1982 to December 1985. NRC Wind Energy Technical Memorandum TM-WE-016. February 1986.